HEAVY HYDROCARBON MAIN INJECTOR TECHNOLOGY

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INTRODUCTION

Over the past several years, interest in a large, low cost, Earth-to-low-orbit launch vehicle system has been growing. One of the key components of this Advanced Launch System (ALS) is a large (500,000 to 2,000,000 lb thrust), liquid rocket, booster engine. To keep the overall vehicle size and cost down, this engine will probably use liquid oxygen (LOX) and a heavy hydrocarbon, such as RP-1, as propellants and operate at relatively high chamber pressures (2000 to 4000 psi) to increase overall performance. Previous LOX/RP-1 booster system engines operated at chamber pressures of 1000 psi or less and had injector performances in the range of 90 to 95% c* efficiencies. The only large scale LOX/RP-1 production engine, the F-1, operated at approximately 1000 psi with a c* efficiency of 92% and a thrust of 1.5 Mlb. In addition, most of the previous LOX/RP-1 booster engines experienced stability problems during development that required extensive efforts to resolve prior to flight operations.

Based on this history and on the new goals of higher chamber pressures and higher performance, a technology program (Heavy Hydrocarbon Main Injector Technology), sponsored by NASA-MSFC, is currently under way at Rocketdyne. The main objective of this 36 month technology effort is to develop a logic plan and supporting experimental data base to reduce the risk of developing a large scale (approximately 750,000 lb thrust), high performance (c* efficiency of 97% or greater at chamber pressures of 2000 to 3000 psi), main injector system. This paper discusses the overall approach and program plan, from initial analyses to large scale, two dimensional combustor design and test, and the current status of the program. Progress to date includes performance and stability analyses, cold flow tests of injector model, design and fabrication of subscale injectors and calorimeter combustors for performance, heat transfer, and dynamic stability tests, and preparation of hot-fire test plans. Related, current, high pressure, LOX/RP-1 injector technology efforts at Rocketdyne are also briefly discussed.

PROGRAM DESCRIPTION

The primary objective of this program is to advance existing LOX/RP-1 main injector technology to a level more adequate to support the development of an engine with the following functional goals:

Parameter	Functional Goal
Chamber pressure	2000 to 3000 psia
Minimum c* efficiency	97%
Stability	+/- 5% of Pc
Thrust level	750,000 lb

The program is based on the concept of a full scale injector made up of multiple isolated combustion compartments (ICCs), each with its own injector, propellant manifolding, and acoustic stability aids. Development of a subscale injector system with the requisite performance, stability, and combustion chamber compatibility characteristics, whose size corresponds to that of a single typical ICC would, minimize problems in developing a full size injector/combustor assembly utilizing similar ICCs.

The approach being used to achieve this objective involves the following steps: analyze and cold flow test several LOX/RP-1 injection concepts; design, fabricate, and hot-fire test (in a 3.5 in. diameter combustor at 2000 to 3000 psi) injectors that have the most promise of meeting the program goals; test the best of these injector patterns in an ICC size (5.7 in. diameter, approximately 40,000 lb thrust) combustor; and perform preliminary design of a 2-D combustor incorporating approximately five ICC units. The 2-D combustor (of approximately 200,000 lb thrust) will be finalized and fabricated in Phase II for testing at the Marshall Space Flight Center (MSFC).

A program logic diagram is presented in Figure 1 and the schedule for the overall effort is shown in Figure 2.
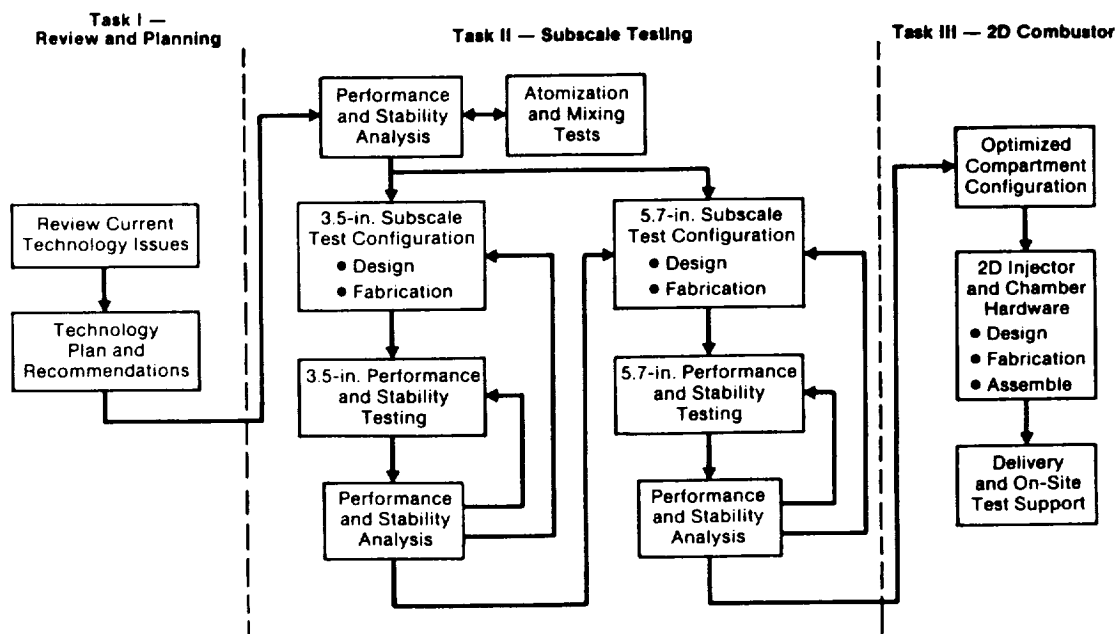
TECHNICAL STATUS

Technology Review

A detailed review of high pressure LOX/RP-1 injector technology was made, which will be included in the program final report. A brief summary is presented herein.

Performance. Results of the very limited experimental work that has been carried out with LOX/RP-1 injectors at high chamber pressure (2000 psi and greater) confirm the inherent difficulty of achieving high performance in combination with stable combustion and acceptable heat flux levels. High performance per se has been demonstrated, but achieving high performance combined with acceptable heat flux and dynamic stability will be difficult.

Stability. Available analytical methods are not able to reliably and consistently predict the damping capability of stability aids,

Task I —
Review and Planning

Task II — Subscale Testing

Task III — 2D Combustor

Performance and Stability Analysis

Atomization and Mixing Tests

Optimized Compartment Configuration

Review Current Technology Issues

3.5-in. Subscale Test Configuration
● Design
● Fabrication

5.7-in. Subscale Test Configuration
● Design
● Fabrication

2D Injector and Chamber Hardware
● Design
● Fabrication
● Assemble

Technology Plan and Recommendations

3.5-in. Performance and Stability Testing

5.7-in. Performance and Stability Testing

Delivery and On-Site Test Support

Performance and Stability Analysis

Performance and Stability Analysis

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Figure 1. Program Logic

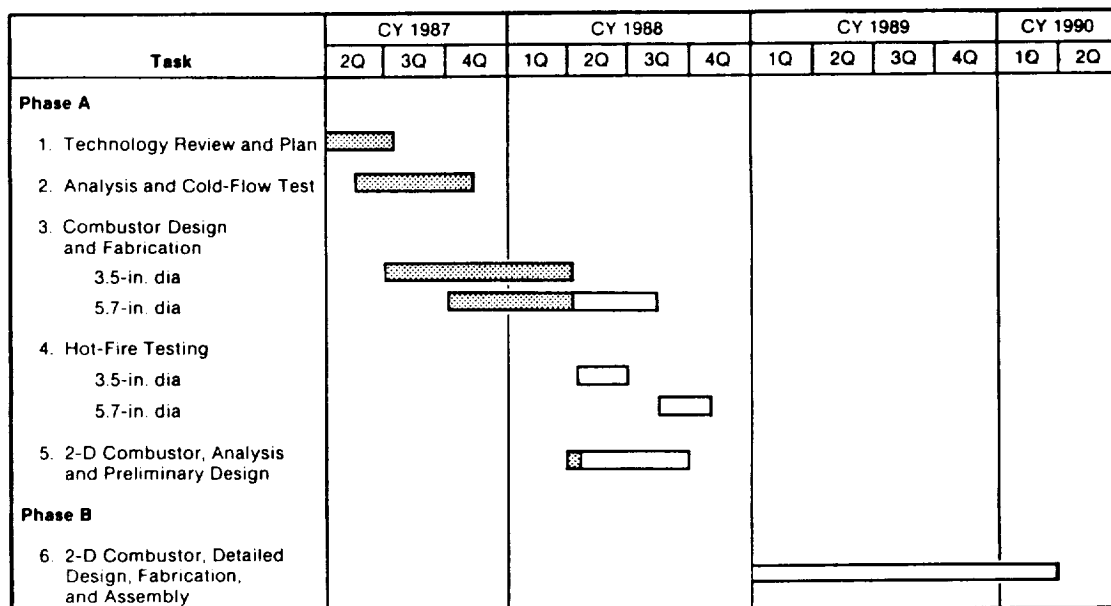| Task	CY 1987			CY 1988				CY 1989				CY 1990	
	2Q	3Q	4Q	1Q	2Q	3Q	4Q	1Q	2Q	3Q	4Q	1Q	2Q
Phase A													
1. Technology Review and Plan	▨												
2. Analysis and Cold-Flow Test		▨											
3. Combustor Design and Fabrication													
3.5-in. dia			▨										
5.7-in. dia				▨									
4. Hot-Fire Testing													
3.5-in. dia					☐								
5.7-in. dia						☐							
5. 2-D Combustor, Analysis and Preliminary Design					▨								
Phase B													
6. 2-D Combustor, Detailed Design, Fabrication, and Assembly								☐					

Figure 2. Program Schedule

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particularly in regimes for which there are no anchoring test data. Neither can the tendency toward instability initiation of a given injection element be reliably predicted at untested operating conditions. Consequently, the likelihood that any injector type would initiate and sustain combustion instability must be predicted as well as possible from both test experience and analysis, and stability aids must be designed on the same basis. The combined effects of injector type and stability aids must be verified by hot-fire testing at the expected operating conditions.

Heat Flux. Chamber heat flux considerations can affect the design of a high pressure LOX/RP-1 injector in several ways. Analyses and background experience indicate that, at present, only a regeneratively cooled, high strength copper alloy combustion chamber would be appropriate for this type of engine. Given that requirement, there are several factors and options that further influence the heat transfer aspects of injector design:

1. Use of RP-1 as regenerative coolant without enhancement limits chamber pressure to the 2000 psi range. Such enhancement techniques are not considered part of injector development technology.

2. Special considerations in the use of RP-1 as coolant relate to coking and erosion. Again, these are important problems but are not included as part of injector technology.

3. If RP-1 is used as coolant, it will probably enter the injector manifold at elevated temperatures, which will be further raised as the RP-1 flows through the injector face. This affects injector design because hot RP-1 increases the possibility of progressive coking and blocking of orifices, particularly if the orifices are small.

4. Cooling with LOX is an alternative to cooling with RP-1. Limited experimental data indicate that such cooling is feasible. It would also raise the maximum feasible chamber sure compared to that with RP-1 cooling, although conflicting estimates have been reported in this regard. The important effect on injector design of using LOX as coolant would be the conversion to a gas/liquid scheme injection from liquid/liquid injection.

5. Hydrogen could also be used as a chamber coolant, which would require a tri-propellant engine system and would permit chamber pressures possibly as high as 4000 psia. The effect on the main injector design of using hydrogen cooling will depend on the particular engine system configuration.

Technology Plan

The review of high pressure LOX/RP-1 injector technology showed that substantial technology advances will be required to meet the goals of high performance, stable combustion, and manageable heat flux.

Because of the difficulties associated with the use of RP-1 as regenerative coolant in a high pressure combustion chamber, it is possible that the cooling method will be modified. The injection process would then involve fluids other than LOX and liquid RP-1, even though the engine remains an LOX/RP-1 system. Depending on the choice of engine cycle and coolant, the main injector may alternatively be a gas/liquid type (GOX/RP-1) or a tri-propellant type (LOX/RP-1/GH2), each depending on a technology base substantially different from that of a liquid/liquid injector. The first task of an injector technology plan is to choose an appropriate cooling technique for the selected LOX/RP-1 engine.

The injection type selection process is indicated in Figure 3. The choice of cycle for the LOX/RP-1 engine, the chamber pressure to be used, and the injection mode will be based on four factors:

- Mission requirements
- Cycle analyses results
- LOX/RP-1 engine experience
- Available cooling methods.
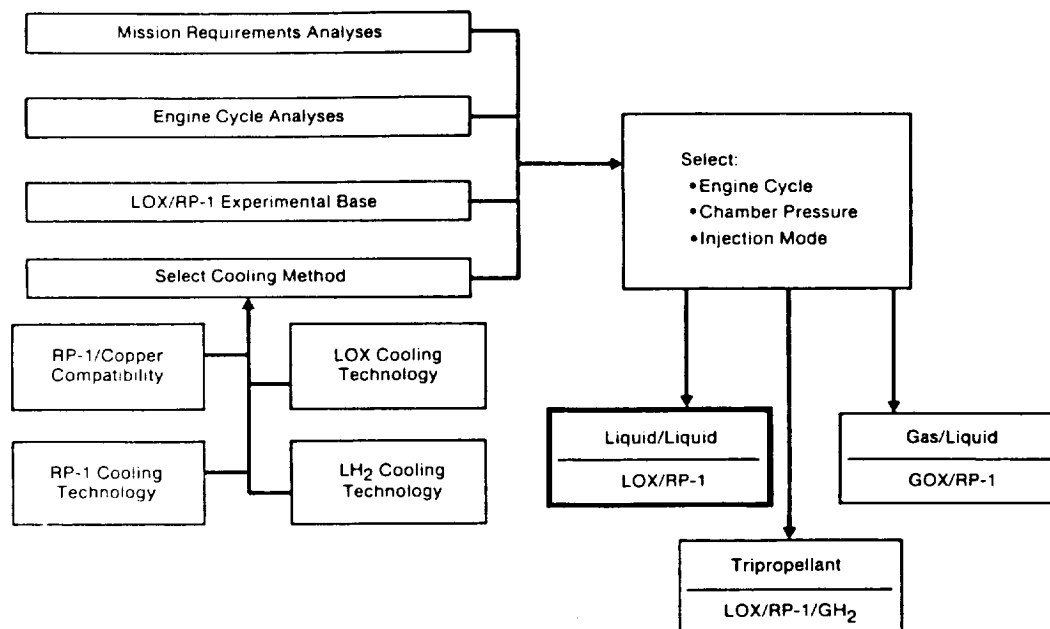
Figure 3. Injector Type Selection   88D-30-370

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INJECTOR PATTERN SELECTION

Candidate Injector Concepts

For this program, only LOX/RP-1 injector types will be considered. Certain advanced engine concepts (e.g., those using LOX or LH2 as coolants) may require injection of other reactants (GOX or GH2) and would therefore need different types of injectors.

A variety of conventional and nonconventional concepts were examined as candidates for a high pressure LOX/RP-1 injector that would meet the stated performance, stability, and heat flux goals. The scope of the present program requires design, fabrication, and testing of two 3.5 in. diameter injectors prior to selection of a pattern for the 5.7 in. diameter and 2-D combustors. Fortunately, the candidate choice has been widened by three additional injector concepts, which will be tested in other experimental investigations of LOX/RP-1 combustors using 3.5 in. diameter hardware at 2000 to 2500 psia chamber pressure. Thus, while only two injectors will be designed and tested in this specific program, the discussion of candidate concepts will cover the following five patterns, which will be included in the selection process.

1. Like impinging elements, H-1 derivative
2. LOX showerhead/fuel doublet configuration
3. O-F-O triplet elements
4. Like impinging doublet elements, circular fans
5. Box pattern, like impinging doublet elements.

Concept No. 1: Like Impinging Elements, H-1 Derivative. The classic LOX/RP-1 injector combining high performance with good stability is a version of the H-1 engine injector configuration (Type 5588). A 3.5 in. derivative of this pattern was selected to serve as a "baseline" to which the other four concepts could be compared. The Type 5588 injector had alternating oxidizer and fuel rings, with primarily a pattern of like impinging oxidizer triplets and fuel doublets. The design included a variety of orifice sizes, impingement distances, and injection angles, most of which were empirical results of extensive test experience.

Downscaling of the large (20.9 in. diameter), low pressure (700 psia), H-1 injector to a 3.5 in., 2000 psia version required numerous compromises. For example, the H-1 injector used baffles as stability aids, whereas the 3.5 in. version uses acoustic cavities around the injector periphery. Consequently, the distance from the outer row of elements to the chamber wall in the 3.5 in. combustor is significantly increased; this may lead to substantially increased recirculation of oxidizer rich gases at the injector face, with higher head end heat flux. Hence, the elements in the outer oxidizer row were angled slightly outward to better fill this mass deficient zone with combustion gas.

Higher chamber pressures require more orifice area per square inch of injector face area. The 3.5 in. injector therefore had smaller and more closely spaced orifices than the H-1 type. Also, the widths of the injection manifold rings were reduced from those in the H-1 to permit as many rows of elements as practical. The outer row of fuel doublets was radially oriented in line with the adjacent row of oxidizer triplets, as in the H-1, but the inner rows contained as many elements as practical, without regard to clocking adjacent rows of fuel and oxidizer, again as in the H-1 design. Nevertheless, even the closer spaced injector pattern is quite coarse and relatively high mixing losses would be expected in the scaled down derivative. This injector is shown in Figure 4.

Concept No. 2: LOX Showerhead/Fuel Doublet Configuration. This concept is illustrated by the corresponding cold flow fixture (Figure 5), which is twice the hot-fire size. It consists of four (shared) fuel fans impinging edgewise onto a central oxidizer showerhead stream. The elements are arrayed in a closely spaced "box" pattern on the injector face (Figure 6). This concept represents an extreme case of delayed atomization and vaporization of the liquid oxygen while maintaining rapid atomization and vaporization of the RP-1. The purpose of this configuration is to extend the combustion zone away from the injector face, which would increase the stability potential. The comparatively long combustion chamber, in combination with the rapid, fine atomization of the fuel, should minimize any decrease in combustion efficiency.

Concept No. 3: O-F-O Triplet Elements. Although use of unlike impinging elements with LOX/RP-1 has traditionally been associated with a strong tendency toward unstable combustion, some recent experimental data indicate that this may be overcome with stability aids such as acoustic cavities. If so, then the high performance levels characteristic of these elements would make them important candidates in the present application. An O-F-O configuration is appropriate rather than F-O-F because the former results in oxidizer and fuel orifices of near equal diameters. As designed, the injector (Figure 7) has large orifices (0.111 in. fuel and 0.125 in. oxidizer) and a comparatively small number of elements to raise the stability potential (see Stability Analysis section).

Concept No. 4: Like Impinging Doublet Elements, Circular Fans. This injector has three rings of like impinging doublet elements, alternating fuel and oxidizer in each ring. The edge impinging fans are parallel to the wall. This differs from the pre-1970 LOX/RP-1 engine injectors, which utilized alternating fuel and oxidizer rings with radial fan orientation. Advanced fabrication techniques were used for this injector to maximize the number of elements for potential high mixing and atomization efficiencies. While radial fans provide a film cooling effect from impingement of the outer row of fuel fans on the wall,
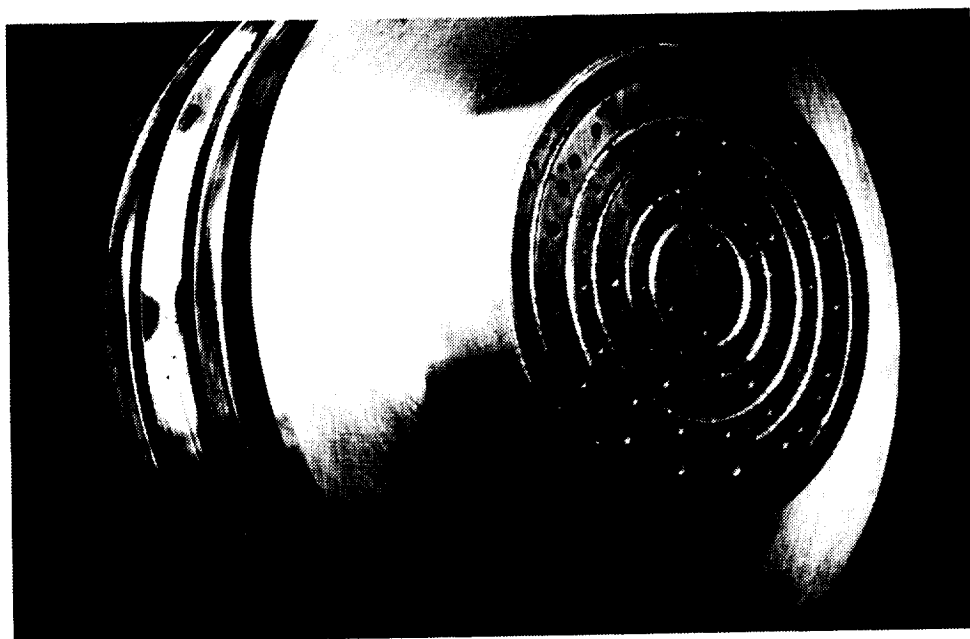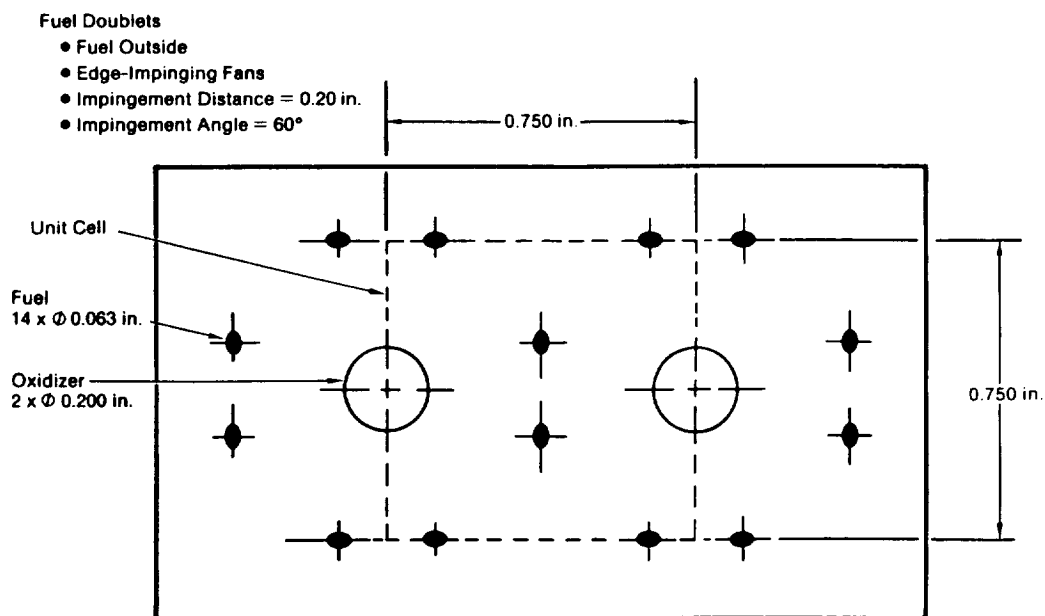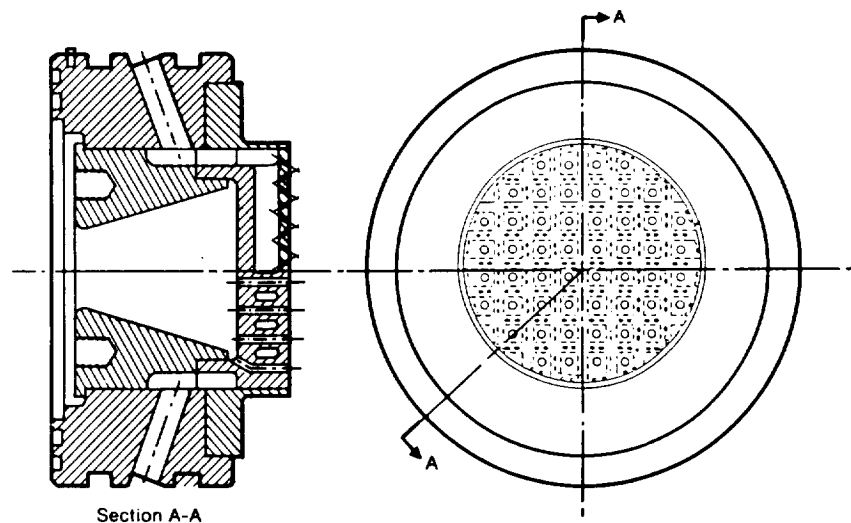
Figure 4. H-1 Derivative Injector

Fuel Doublets
- Fuel Outside
- Edge-Impinging Fans
- Impingement Distance = 0.20 in.
- Impingement Angle = 60°

Unit Cell

Fuel
14 x Ø 0.063 in.

Oxidizer
2 x Ø 0.200 in.

0.750 in.

0.750 in.

Figure 5. LOX Showerhead Cold Flow Fixture

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Injector Orifices	
LOX	RP-1
32 at 0.096	208 at 0.030
20 at 0.106	16 at 0.040
	8 at 0.025

Section A-A

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Figure 6. LOX Showerhead Injector Assembly
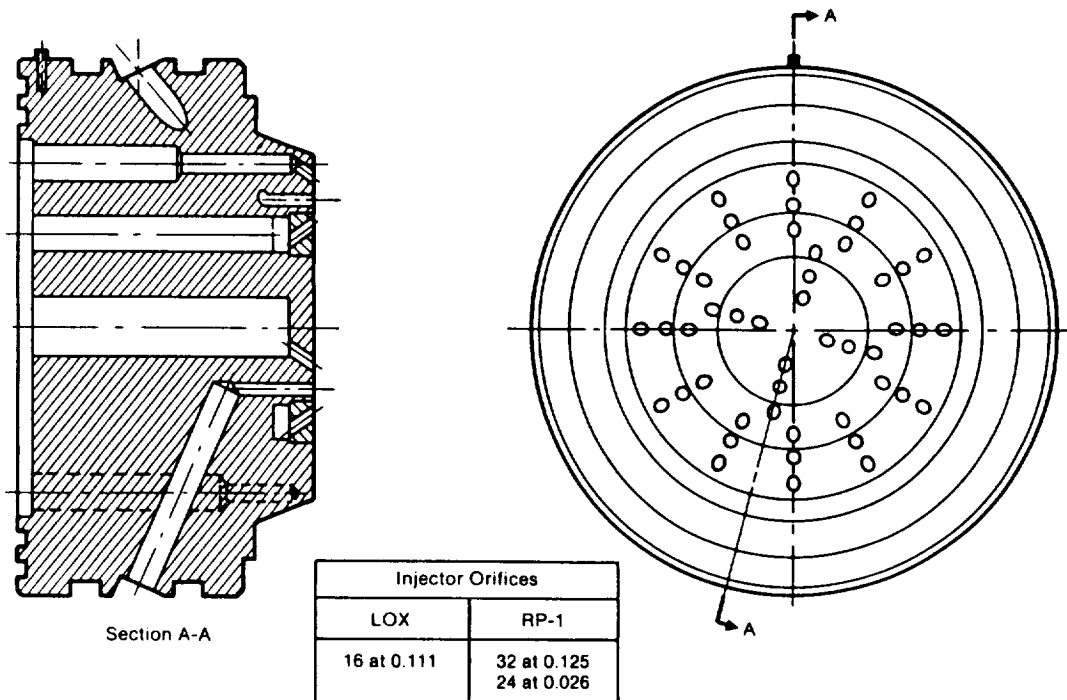
Injector Orifices	
LOX	RP-1
16 at 0.111	32 at 0.125
	24 at 0.026

Section A-A

Figure 7. O-F-O Triplet Injector Assembly   88D-30-367

circular fans do not provide this outer fuel offset. However, film cooling can be added to the pattern for improved chamber head end cooling and compatibility, if required. This injector (60 LOX doublets, Do = 0.064 in.; 60 RP-1 doublets, Df = 0.042 in.) is shown in Figure 8.

Concept No. 5: Box Pattern, Like Impinging Doublet Elements. This injector concept utilizes a central, like impinging, LOX doublet encompassed by four (shared) like impinging, fuel doublets in a square "box" pattern. The corresponding cold flow fixture (with twice the hot-fire dimensions) is shown in Figure 9. Two of the fuel fans edge impinge on the LOX fan; the other two are flat impinging. The square box is repeated across the injector face, with alternating oxidizer fan orientations in adjacent squares (Figure 10).

This design provides good edge impinging characteristics while keeping the oxidizer spray encased in fuel sprays. The oxidizer orifices (Do = 0.079 in.) are significantly larger than the fuel orifices (Df = 0.033 in.) to facilitate rapid fuel vaporization while delaying oxidizer vaporization. This simulates to a degree the characteristics of a coaxial element, which generally provides high performance, stable combustion, and good chamber compatibility. Delaying the LOX vaporization should be a stabilizing influence without undue performance degradation, even with the relatively coarse injection pattern.

Stability Analyses

Acoustic combustion stability analyses were carried out for various injector types in 3.5 and 5.7 in. diameter chambers utilizing the Crocco sensitive-time-lag technique (Ref. 1), the Priem stability parameter calculation (Ref. 2), and the empirically derived Webber correlation (Ref. 3). Results of these analyses pertaining to the injectors discussed in the preceding section are summarized below.

Sensitive-Time-Lag Analyses, 3.5 in. Chamber. These analyses were made for injector concept No. 1 (like impinging elements, H-1 derivative), injector concept No. 2 (LOX showerhead/RP-1 doublets), injector concept No. 3 (O-F-O triplet elements), and injector concept No. 5 (like impinging doublets, box pattern), with and without 'L' shaped Helmholtz cavities. A recent computer code (Ref. 4) was used for these calculations, with the following inputs: LOX/RP-1 reactants at 2000-psia chamber pressure, acoustic cavity gas temperature equivalent to 60% of chamber temperature, and combustion zone length to chamber radius ratio (Zc/rch) dependent on the injection pattern. The code computes the neutrally stable combustion response in the form of a pressure interaction index, n, as a function of the sensitive time lag, tau. Injector response was estimated from standardized correlations of experimental data (Ref. 5).* For each case, the injector response, including estimated error bands, was plotted on the same figure as the combustor response. The combustor system is considered to be stable if
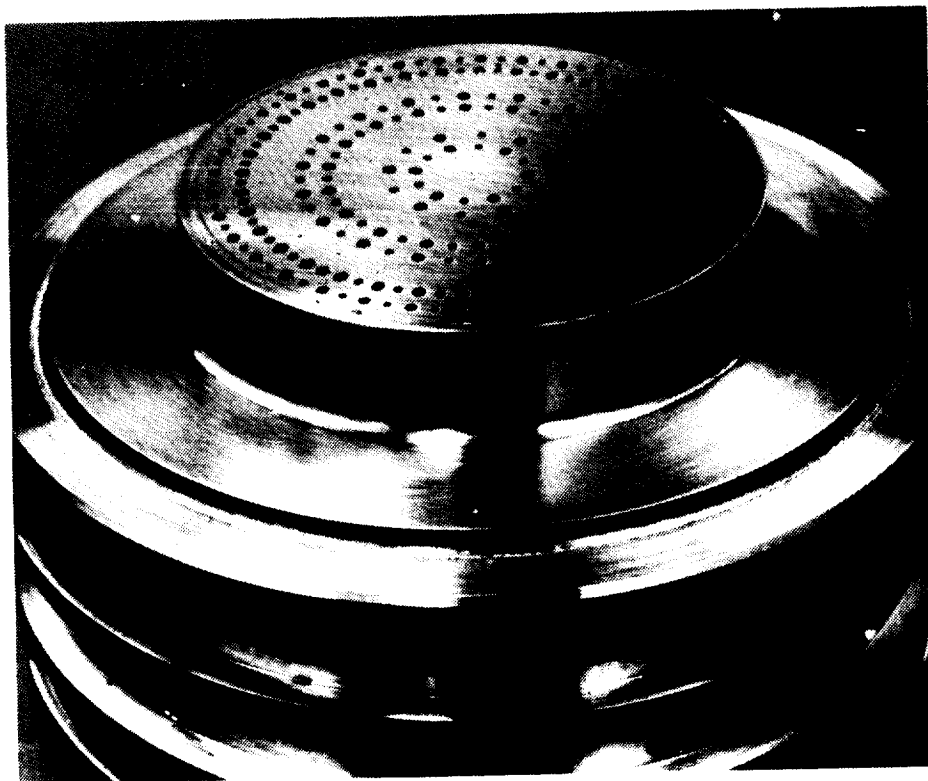
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Figure 8. Like Edge Impinging Circular an Injector

Oxidizer and Fuel Doublets
- Alternating Edge-Impinging LOX Fans
- Impingement Distance = 0.325 in.
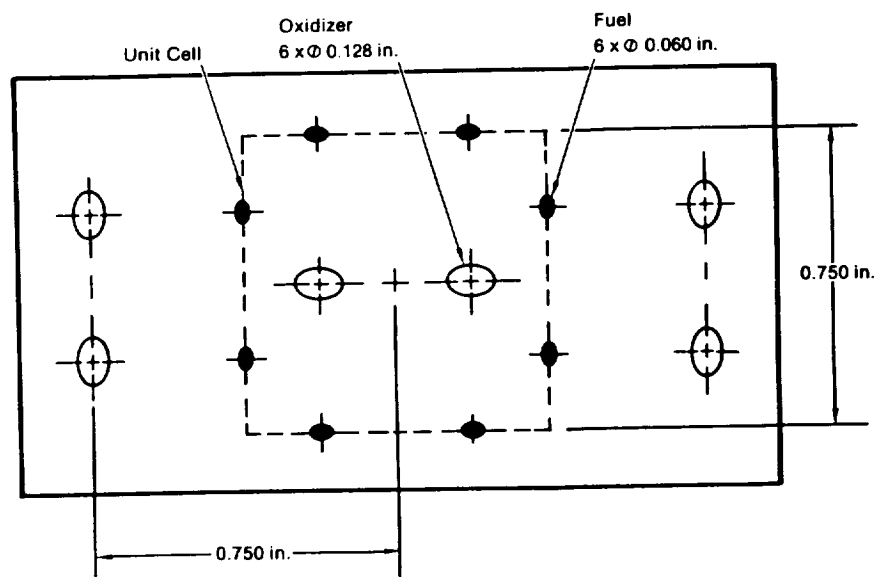- Impingement Angle = 60°

Figure 9. Box Pattern Doublet Cold Flow Fixture   88D-30-371

Figure 10. Box Pattern Doublet Injector Insert

the injector response falls below that of the combustor curve.

Response curves of injector concept No. 1 are shown in Figure 11. This injector is predicted to be marginal without acoustic cavities and stable with cavities. The curves for injector concept No. 2, shown in Figure 12, indicate instability without acoustic cavities and probable stability with cavities. (In this case, the response calculations with cavities are incomplete and require extrapolation due to convergence problems associated with longitudinal modes whose combustion responses

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* These correlations separate unlike impinging patterns from like impinging (or showerhead) patterns, with the latter yielding tau values up to five times larger than the former. Use of such high values of tau leads to the prediction that 1-T mode instabilities would not occur even without acoustic cavities. Further, the like impinging or showerhead correlation is based on five propellant combinations, only one of which is LOX/RP-1. Consequently, to provide a conservative "best estimate" for all the injectors, only the unlike impinging correlation was used, with the recognition that it might predict instability where none would actually occur.

are close to, or overlap, the first tangential mode). Injector concept No. 3 shown in Figure 13, is predicted to be stable even without acoustic cavities. Injector concept No. 5 is indicated to be stable with acoustic cavities and unstable without them (Figure 14). Injector concept No. 4 should show similar stability response as injector concept No. 5 and can also be represented by Figure 14.
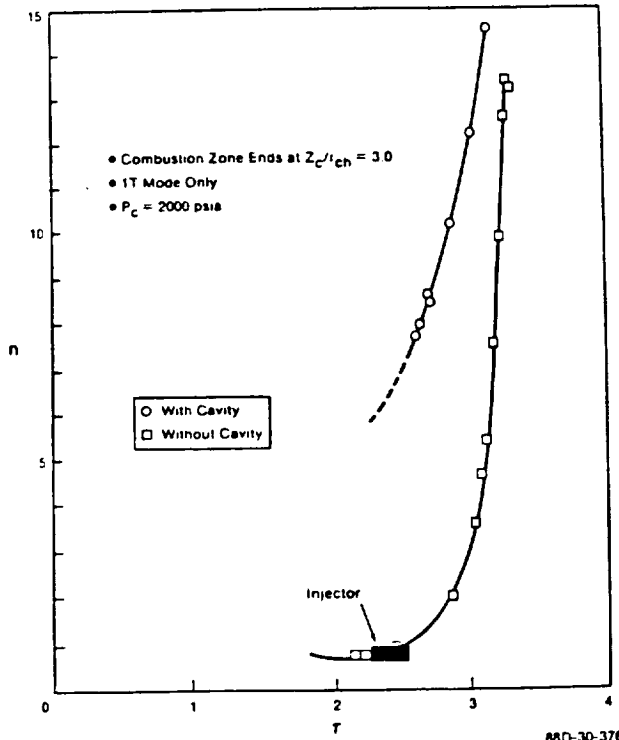

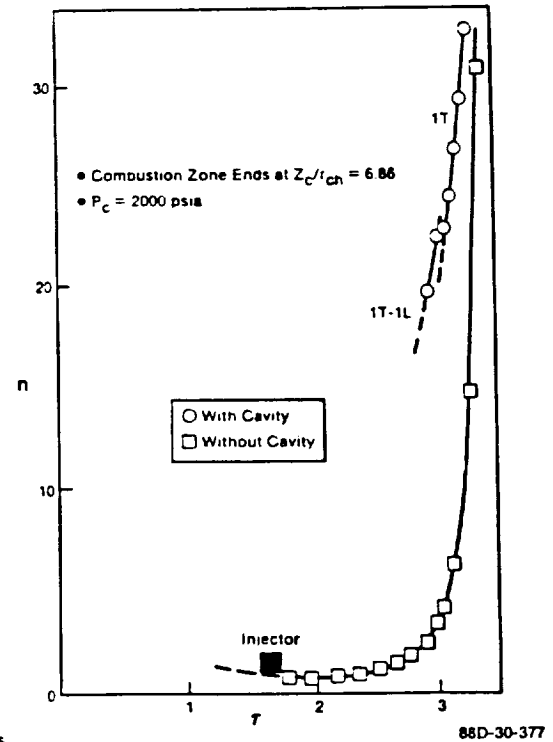
Figure 11. n-tau Curves for Injector No. 1, H-1 Derivative

Figure 12. n-tau Curves for Injector No. 2, LOX Showerhead

Sensitive-Time-Lag Analyses, 5.7 in. Chamber. The acoustic cavity configuration used for the 5.7 in. chamber computations was a quarter wave slot absorber, which is appropriate to the ICC concept and will be used in the 5.7 in. diameter and 2-D test combustors. Calculations were made for like doublet injectors with three sets of orifice sizes and for O-F-O triplet injectors with two sets of orifice sizes. Input parameters for the injector, combustion chamber, and acoustic cavities are listed in Table 1. The n-tau response curves indicate that like doublet injectors with 0.030 , 0.060 , or 0.100 in. fuel orifice diameters would probably be unstable in a 1-T, 2-T, 1-R, or 1-T/1-R mode if operated without acoustic absorbers. The O-F-O triplet injectors with 0.100 or 0.125 in. fuel orifice diameters are predicted to be marginally unstable, with instability probably in the 1-T mode, without acoustic absorbers.
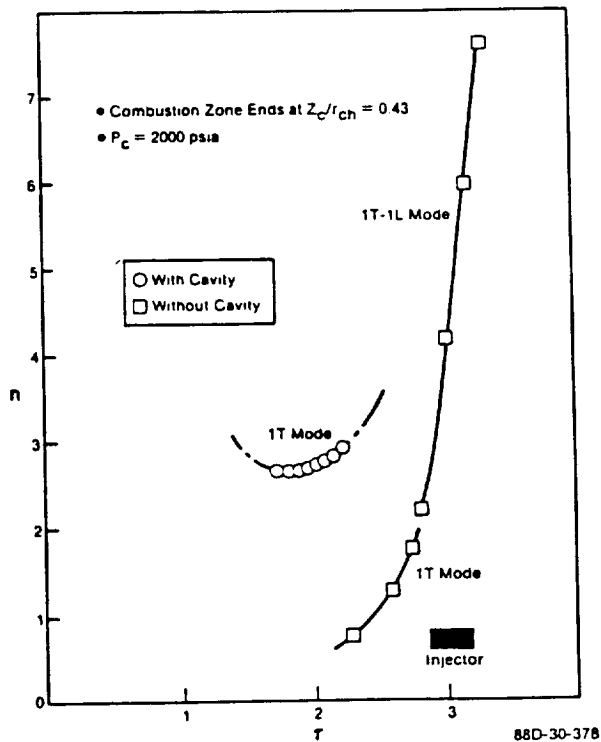
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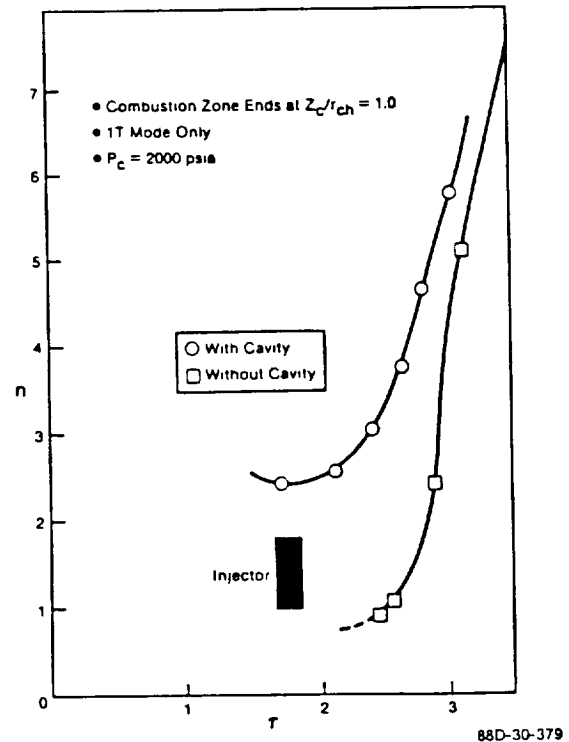**Figure 13. n-tau Curves for Injector No. 3, O-F-O Triplet**

Figure 14. n-tau Curves for Injector No. 5, Like-Doublet Box

With quarter wave slot absorbers tuned to the 1-T, 2-T, or 1-R modal frequencies, the like doublet injector with 0.030 in. fuel orifices diameter is predicted to be unstable. The 0.060 in. fuel orifice diameter like doublet injector would probably be stable with 10% open area quarter wave slot absorbers tuned to the 2-T mode, while the 0.100 in. fuel orifice configuration would have a substantial stability margin with a 2-T tuned slot and a good margin with a 1-T tuned slot.

Both triplet injector configurations are predicted to have good stability margins when used with quarter wave slot absorbers tuned to the 1-T modal frequency.

Priem Analyses, 5.7 in. Chamber. The Rocketdyne SDER code computes propellant vaporization rates and the Priem stability parameter, or normalized pressure disturbance (Ap), as a function of chamber length. The computations are based on local vaporization rates, flow conditions, and curve fitted stability correlations. The value of Ap at a given location is the normalized pressure disturbance required to excite an instability; the higher the value of Ap, the greater the margin of stability.

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Table 1. Sensitive Time Lag Analysis, Input Parameters

Injector Configurations			
Element Type	D_o (in.)	D_f (in.)	Z_c/r_c (80% Combustion)
Like doublets	0.050	0.030	0.78
	0.100	0.060	1.10
	0.166	0.100	1.37
O-F-O triplets	0.100	0.100	0.65
	0.125	0.125	0.72

Combustion Chamber Parameters	
D_{cham} = 5.66 in.	P_c = 2000 psia
D_{throat} = 3.58 in.	L_{cham} = 19 in.
Sonic velocity = 3979 ft/s	M.R. = 2.80
Mach No. at start of convergence = 0.246	

Quarter-Wave Cavities	
Tuning Mode	Cavity Depth (in.)
1-T	1.328
2-T	0.800
1-R	0.638

A Priem neutral stability curve generally exhibits a minimum point caused by the minimum gas-to-droplet relative velocity characteristic of all impinging jet elements. The chamber location at which the minimum occurs is the most sensitive zone for stability. The chamber wall length should therefore extend well beyond this point. For the like doublet injectors, the sensitive zones were found to be at approximately 1.2, 1.8, and 2.3 in. from the injector face for fuel orifice diameters of 0.03, 0.06, and 0.10 in., respectively. For the O-F-O triplet injectors, the neutral stability curves for 0.100 and 0.125 in. orifices diameters are practically identical. The sensitive zone is approximately 1.1 in. from the injector face, which is less than those of any of the like doublet configurations because of the higher vaporization rate of the triplets.

Webber Correlations, 3.5 in. Chamber. The Webber correlation is based completely on an empirical examination of the acoustic mode combustion instabilities encountered in a large variety of rocket engines. A dimensional probability factor, I, is defined and is directly proportional to the diameter of the chamber or baffle compartment and the cube root of chamber pressure and inversely proportional to the average diameter of the injection orifices. Based on correlated values

of I, all five candidate injector configurations are predicted to be stable when used with acoustic cavities. An O-F-O triplet configuration with large orifices (diameters on the order of 0.10 in.) is predicted to be stable without acoustic cavities. Since this correlation takes no account of the effects on combustion stability of important factors such as element type and propellant combination, it should be regarded only as a rough guide to possible high risks of instability.

To summarize, the stability analyses indicate that all the candidate LOX/RP-1 injectors would probably be stable with properly tuned acoustic cavities and marginally stable or unstable without cavities. The O-F-O triplet pattern with large orifices is predicted to have the largest margin of stability.
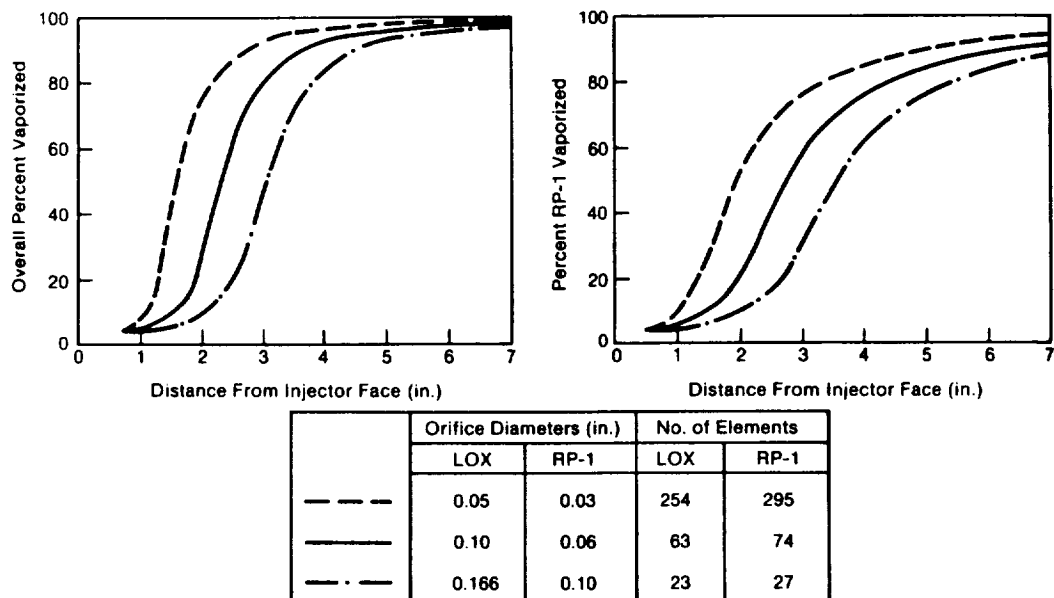
Performance Analyses

Vaporization efficiencies of the three like doublet and two O-F-O triplet injector configurations listed in Table 1 were estimated for LOX/RP-1 at 2000 psia chamber pressure and 2.8 mixture ratio, as functions of distance from the injector face in a 5.7 in. diameter chamber, with the Rocketdyne SDER computer code.

Figure 15 shows the fraction of injected propellants vaporized as a function of distance from the injector face for the three sets of orifice sizes of the like doublet element configuration. One set of curves includes LOX vaporization while the other is for RP-1 only. The initial point for all the curves was taken as 4% vaporization at 0.5 in. from the face. The vaporization rate increases at the start, until the droplets are heated to the propellant critical temperature, after which the rate is lower because of the progressive decrease in droplet mass. If only RP-1 vaporization is considered to be the controlling factor in the extent of combustion, the estimated efficiencies at 4 in. from the injector are 62, 76, and 86%, for the 0.100 , 0.060 , and 0.030 in. fuel orifice diameters, respectively.

The SDER method of calculating droplet diameters produced by triplet injectors includes a factor of 0.2, which was established when the code was anchored to experimental data from hypergolic propellants. Since this factor may not be applicable to LOX/RP-1, calculations for the triplet element injectors were made with and without its inclusion. Propellant vaporization rates for both O-F-O triplet injector configurations are shown in Figure 16. Again, one set of curves includes both propellants while the other set is for RP-1 alone. The effects of including the 0.2 factor are also indicated. In the most conservative estimate, the indicated extent of combustion completion at 4 in. from the injector face is approximately 90% for both the 0.125 and 0.100 in. orifices.

	Orifice Diameters (in.)		No. of Elements	
	LOX	RP-1	LOX	RP-1
– – –	0.05	0.03	254	295
———	0.10	0.06	63	74
—— · ——	0.166	0.10	23	27

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Figure 15. SDER Vaporization Analyses of Like Doublet Injectors

Cold Flow Tests

A series of cold flow mixing tests was carried out with simulated propellants on five model injectors to determine their mixing characteristics and comparative mixing limited c* efficiencies.   Of the five injector patterns tested, two represented configurations that will be included in the hot-fire candidate selection process; the other three are configurations that were not selected for hot-fire.   The two hot-fire candidates were injector concept No. 2 (LOX showerhead/fuel doublet configuration, Figure 5) and injector concept No. 5 (box pattern, like impinging doublet elements, Figure 9). The models that will not be hot-fired include a LOX showerhead with six (shared) RP-1 doublets around it in a hexagonal pattern (Concept A, Figure 17) and two models with LOX like quadlets (which form a star shaped spray), one with four (shared) fuel fans flat impinging on the oxidizer spray (Concept B, Figure 18) and the other with four (shared) fuel fans edge impinging on the oxidizer spray (Concept C, Figure 19).
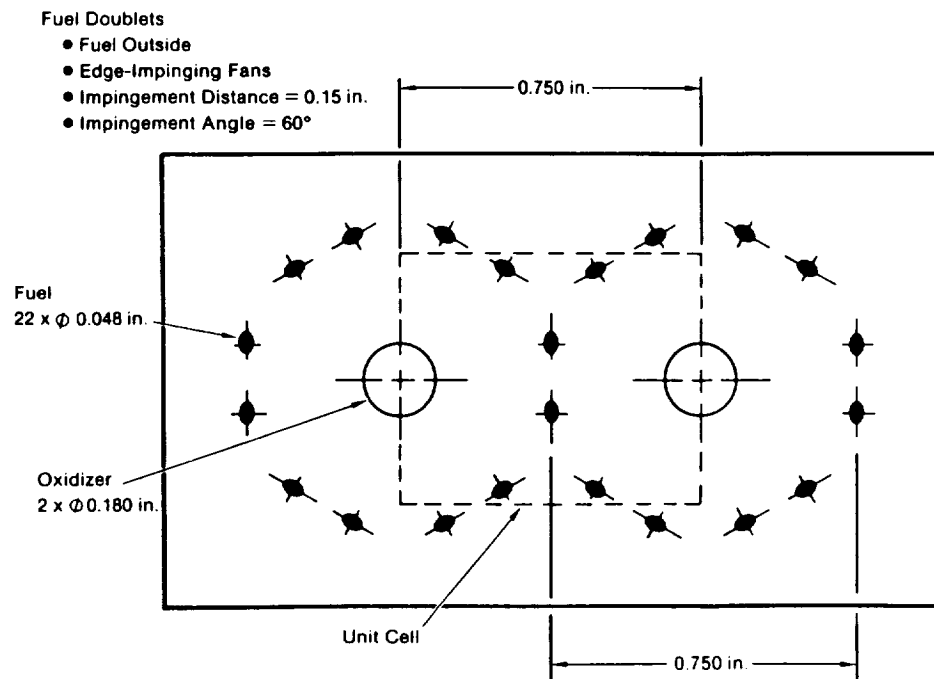
The injector models for the cold flow tests were fabricated from transparent acrylic plastic to give low cost units that permitted visual inspection of the orifices and manifolds. The models were sized at twice the hot-fire scale; i.e., each model was a 2X photographic enlargement of a pattern that would be applicable to a 3.5 in. diameter,

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	Orifice Diameter (in.)	No. of Elements
– – – – –	0.10	62
————	0.125	40
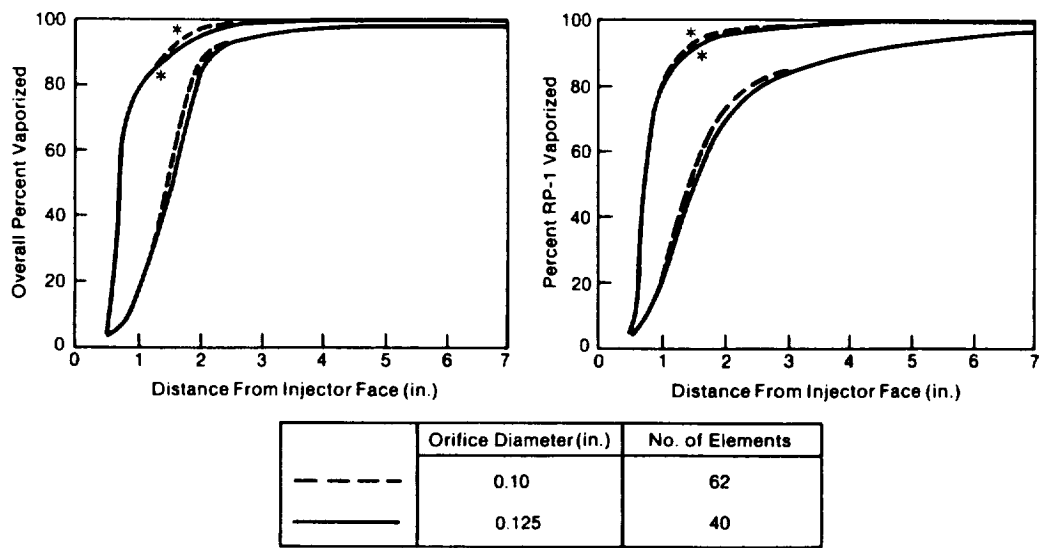
*Droplet diameter method corrected by 0.2 (standard SDER method)

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Figure 16. SDER Vaporization Analyses of O-F-O Injectors

Fuel Doublets
 ● Fuel Outside
 ● Edge-Impinging Fans
 ● Impingement Distance = 0.15 in.
 ● Impingement Angle = 60°

Fuel
22 x ⌀ 0.048 in.

Oxidizer
2 x ⌀ 0.180 in.

Unit Cell

0.750 in.

0.750 in.

Figure 17. LOX Showerhead Hex Pattern Cold-Flow Fixture 88D-30-373

Fuel Doublets
- Fuel Outside
- Flat Fans
- Impingement Distance = 0.20 in.
- Impingement Angle = 60°

Oxidizer Quadlet
- Impingement Distance = 0.56 in.
- Impingement Angle = 60°

0.750 in.

Unit Cell

0.458 in.

0.750 in.

Oxidizer
4 x Ø 0.100 in.

Fuel
8 x Ø 0.063 in.
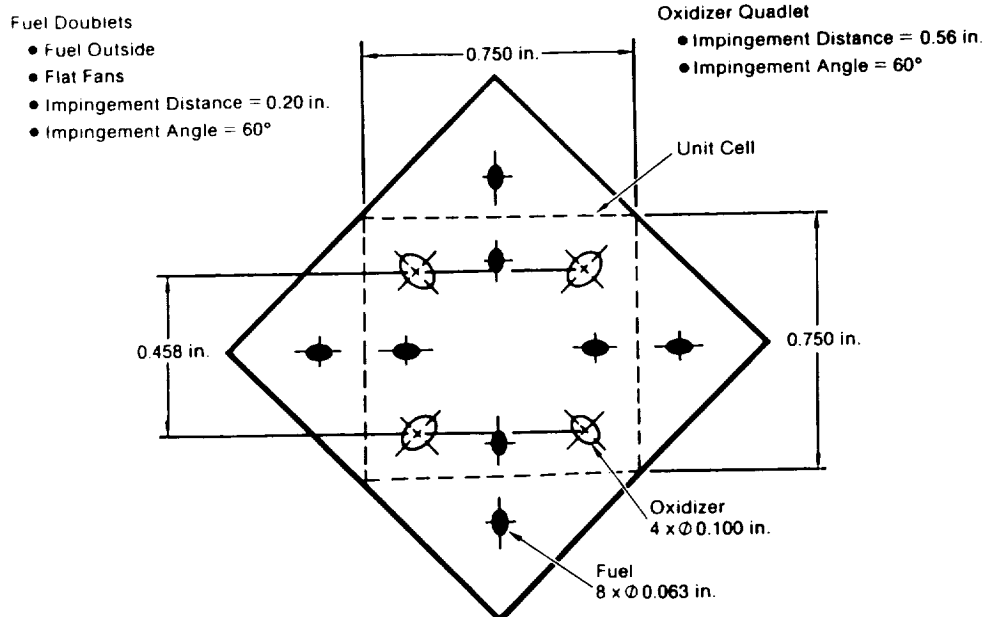
88D-30-374

Figure 18. LOX Quadlet Box Pattern,
Flat Fan, Cold Flow Fixture

Fuel Doublets
- Fuel Outside
- Edge-Impinging on LOX Star
- Impingement Distance = 0.20 in.
- Impingement Angle = 60°

Oxidizer Quadlet
- Impingement Distance = 0.50 in.
- Impingement Angle = 40°

0.750 in.

Oxidizer
4 x Ø 0.100 in.

0.750 in.

Fuel
8 x Ø 0.063 in.
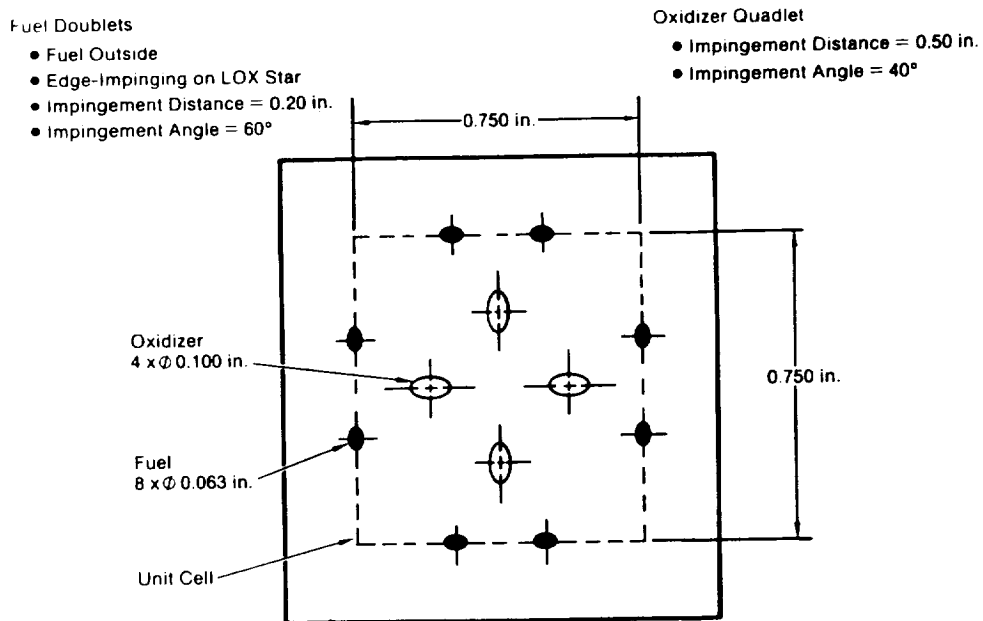
Unit Cell

Figure 19. LOX Quadlet Box Pattern,
Edge Impinging, Cold Flow Fixture

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2500 psia, LOX/RP-1 combustor. This gave a 0.75 in. model unit cell, or pattern repeat logic, for adequate resolution of the flow fields. The corresponding hot-fire injectors would have 0.375 in. unit cells and orifice diameters one half those of their cold flow counterparts.

The cold flow mixing tests were carried out with 1-1-1 trichloroethane and water as simulants for LOX and RP-1, respectively. The injector model was mounted 2 in. above the collection grid of 0.125 in. square tubes so that the 0.75 in. square unit cell was directly over a 6x6 array of tube inlets. A fast acting shutter over the tube inlets limited each test to six seconds of steady state flow. The liquids were collected in individual cylinders for measurement of volumes. The Rupe mixing efficiency index, Em, which is a mass weighted summation of the variations of local mixture ratio from the overall average mixture ratio, was calculated for each injector model. A mixing limited, mass weighted, c* parameter was also calculated by summing the products of the collected sample mass fraction and the theoretical c* value in each tube; a mixing limited c* efficiency value was obtained as the ratio of this parameter to the theoretical c* at the overall mixture ratio. This efficiency is usually significantly higher than Em. It is impacted by the shape of the c* mixture/ratio curve and the overall mixture ratio and indicates the comparative effect of mixing deficiencies on hot-fire performance.

Cold flow test results are briefly summarized in Table 2. Injector concept No. 5 (box pattern, like impinging doublet elements) gives the most efficient mixing of the tested patterns.

Injector Selection

The injector pattern to be used in the 5.7 in. combustor and in the ICC chambers of the 2-D combustor will be selected on the basis of the test results obtained in the 3.5 in. combustor, impacted by the results of the various analyses.

Table 2. Summary of Cold Flow Mixing Results

Injector Concept Model	Unit Cell Characteristics		
	M.R.	E_m	c* Mixing Efficiency
No. 2: LOX showerheat/fuel doublet configuration	3.2	0.59	0.78
No. 5: Box pattern, like-impinging doublet elements	3.2	0.81	0.93
A: LOX showerhead with six (shared) RP-1 doublets	3.0	0.54	0.74
B: LOX like-quadlets with four flat-impinging fuel fans	3.7	0.32	0.60
C: LOX like-quadlets with four edge-impinging fuel fans	2.8	0.60	0.78

Subscale Test Hardware

The hot-fire tests will be carried out with segmented, water cooled, calorimeter combustors. Schematic sketches of the 3.5 and 5.7 in. assemblies are shown in Figures 20 and 21, respectively. The basic designs of these assemblies are the same, differing only in two minor respects:

- The chamber spool lengths in the 3.5 in. combustor are identical (6 in.) while different lengths (8 and 4 in.) are used in the 5.7 in. assembly

- The 8 in. chamber and the throat spools in the 5.7 in. combustor are flanged, while in the 3.5 in. assembly they are not.

Injectors. Two injectors will be tested in this program (injector concept No. 2, LOX showerhead/fuel doublet configuration and injector concept No. 3, O-F-O triplet elements). The three additional injector concepts described in the Candidate Injector Concept section will be tested in other programs. All of the injectors are fabricated from oxygen free, high conductivity (OFHC) copper as cylindrical inserts that fit into the fuel manifold. The injectors are cooled only by the reactants flowing through them.

Chamber Sections. Each calorimeter chamber spool consists of a channeled Narloy-Z liner within a stainless steel jacket. The circumferential cooling channels permit measurements of heat flux along the chamber axis. A 3.5 in. chamber section is shown in Figure 22.

Throat Sections. The contraction ratio in both the 3.5 and 5.7 in. combustors is 2.5. Both throat spools also consist of Narloy-Z cores in stainless steel jackets, with circumferential cooling channels to allow measurements of axial heat flux. The overall assembly with 2 spool sections installed has 28 individual cooling circuits. A 3.5 in. throat
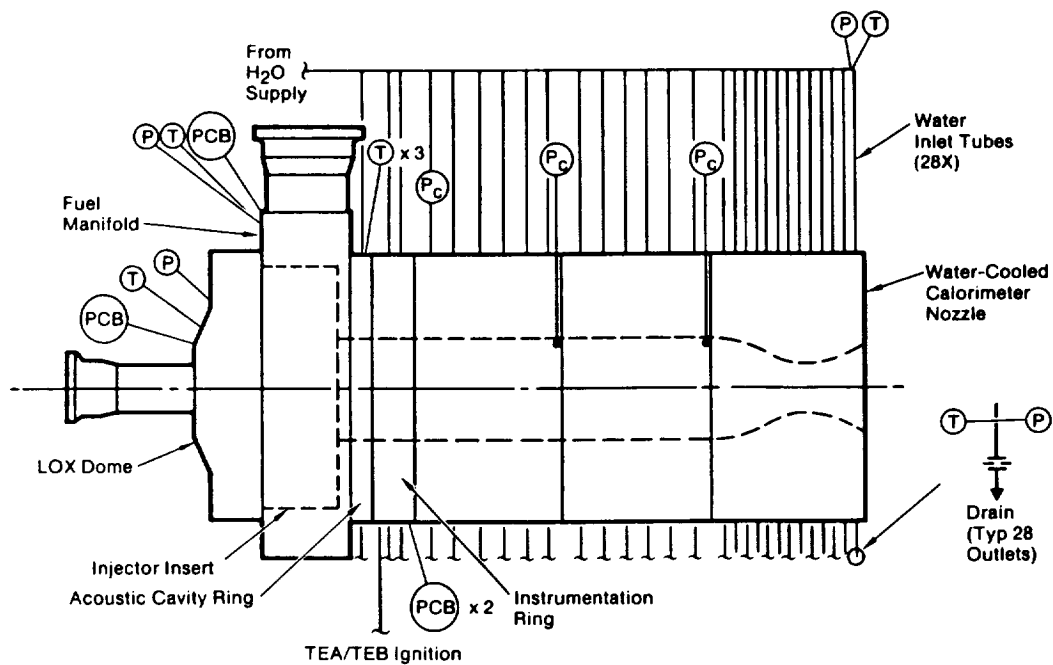
88D-30-382

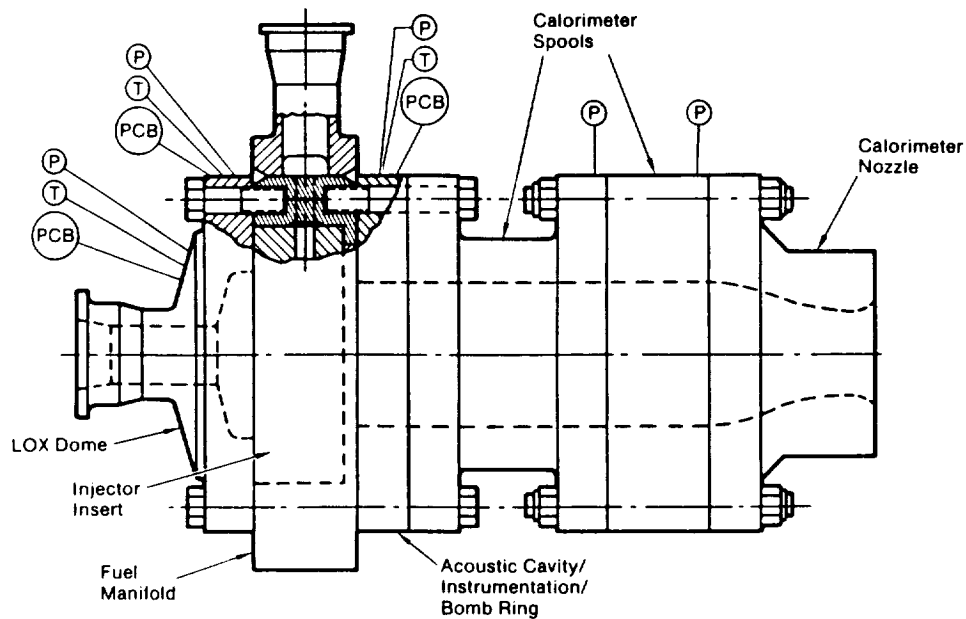Figure 20. 3.5 in. Subscale Calorimeter Combustor Assembly

Figure 21. 5.7 in. Subscale
Calorimeter Combustor Assembly

88D-30-383

spool is shown in Figure 23.

Auxiliary Combustor Components. Auxiliary combustor components are positioned between the injector and the first chamber spool. They include a water cooled, OFHC copper, acoustic cavity ring (Figure 24), which forms seven acoustic cavities around the injector periphery. Cavities with varying open area are available, all tuned to the first tangential mode of oscillation.

A water cooled instrumentation ring (Figure 25) downstream of the acoustic cavity has ports for static and high frequency pressure measurements and for introduction of TEA/TEB igniter. An uncooled instrumentation/bomb ring is also available that has, in addition, a port for mounting a stability rating bomb in tests of dynamic stability.

Subscale Test Plan

The test matrix logic for each injector is the same. As indicated in Figure 26, the matrix includes three or four performance and heat transfer tests followed by two or three dynamic stability tests. The first set will be carried out at 2000 psia chamber pressure and mixture ratios of 2.4, 2.8, and 3.2; one optional test at higher chamber pressure may then be conducted. The first bomb test will be made at nominal conditions, followed by a second one at higher chamber pressure and/or off nominal mixture ratio. If instability occurs in any of the tests, the acoustic cavities will be modified in an attempt to eliminate the observed modes. If the injector is dynamically stable with acoustic cavities, a test without cavities will be carried out at the end of the series.

2-D Combustor Design

Preliminary design of a 2-D LOX/RP-1 combustor will be the final task of the first phase of this program. This combustor will be used primarily to determine the dynamic stability of a selected injector concept in a multi ICC unit that simulates the acoustic characteristics of a full scale 3-D combustor. The design thrust level is on the order of 200,000 lb for the 2-D unit. The workhorse type 2-D combustor configuration will include five separated chambers with individual injectors and acoustic cavities. The requirements and characteristics of a 3-D, ICC combustor will be primary considerations of the design of the 2-D chamber.

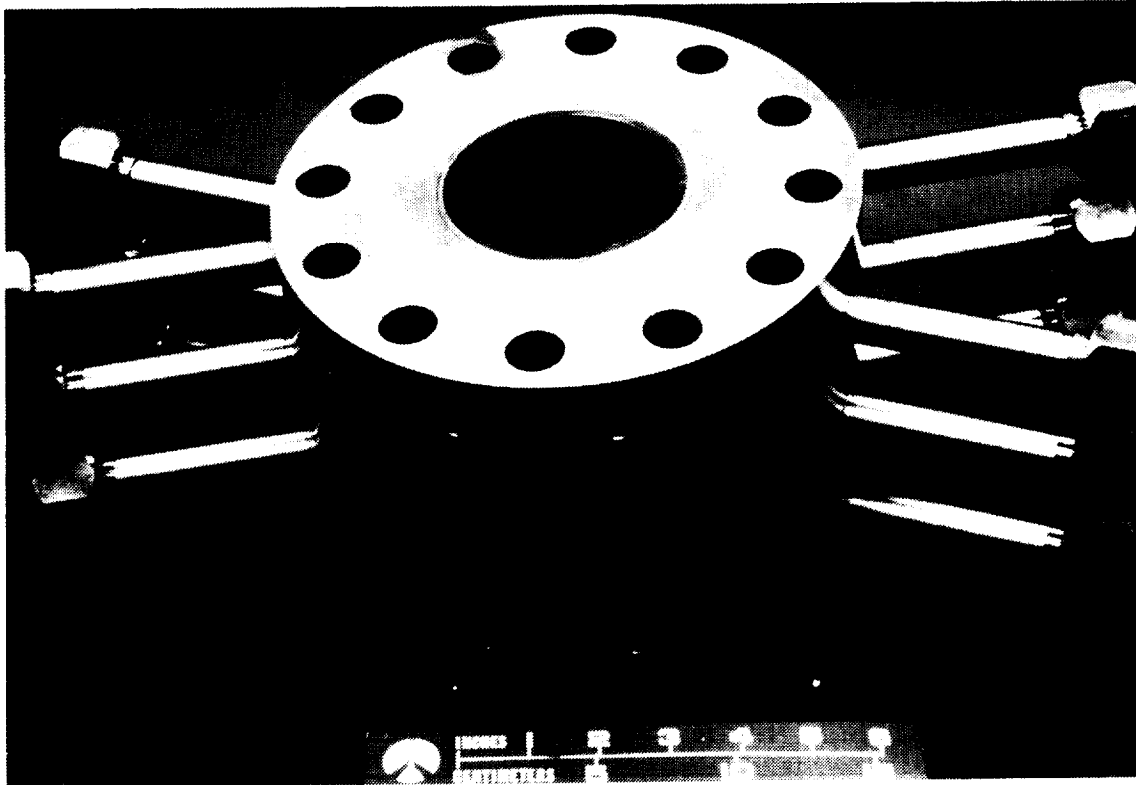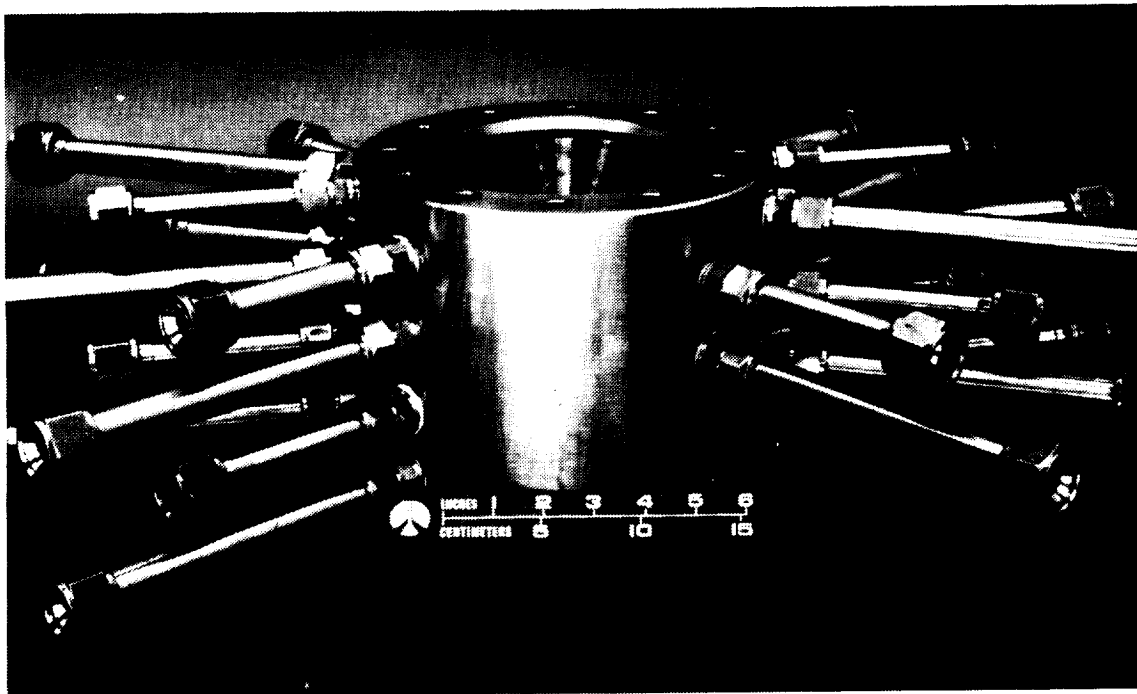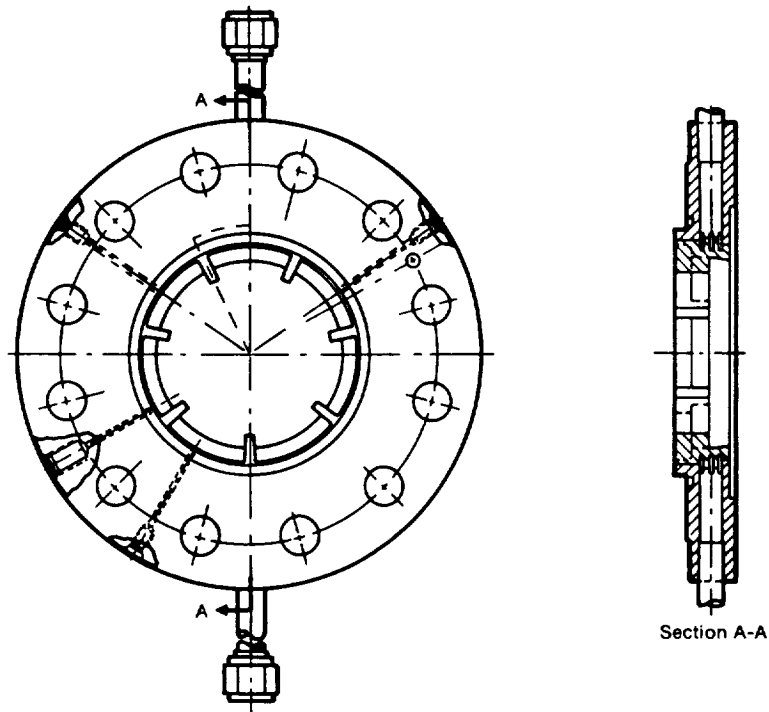Figure 22. Calorimeter Chamber Spool Assembly

Figure 23. Calorimeter Throat Section Assembly

Figure 24. Water Cooled Acoustic Cavity Assembly

88D-30-385
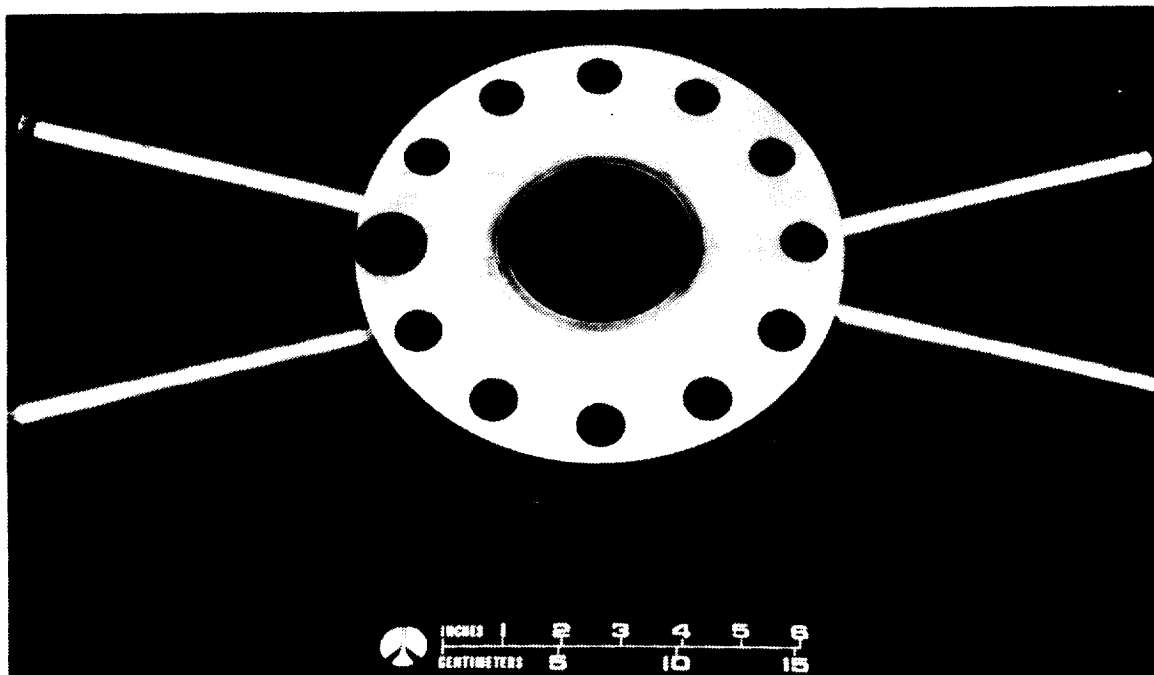

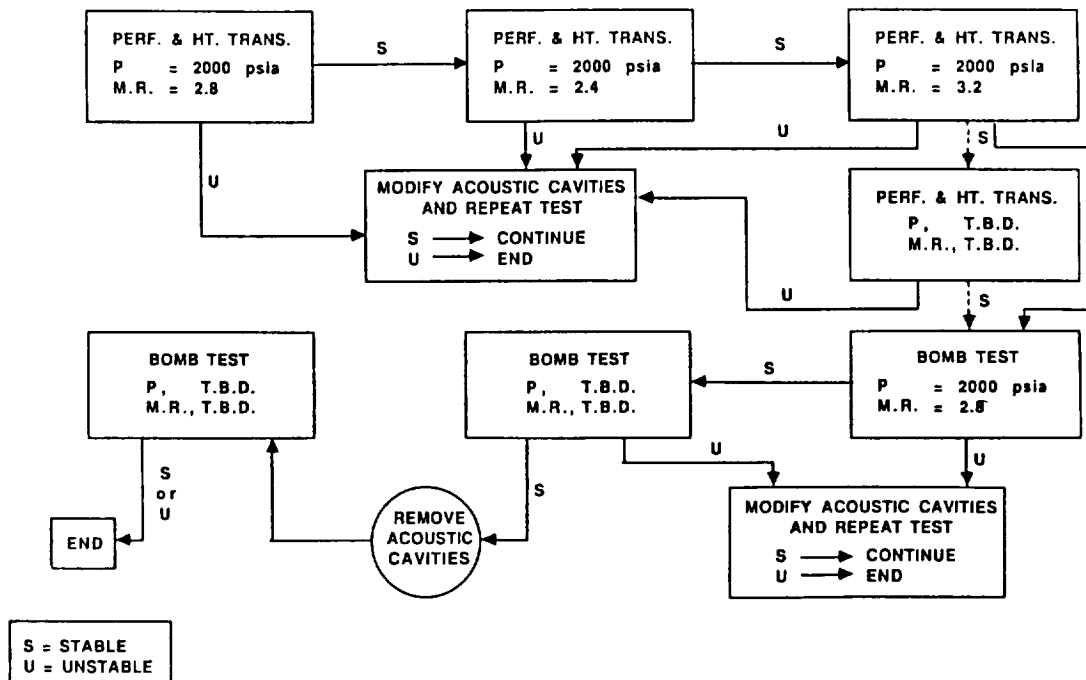Figure 25. Water Cooled Instrumentation Ring

Figure 26. Subscale Hot-Fire Test Logic   88D-30-384

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